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Evidence for ground-rupturing earthquakes on the Northern Wadi Araba fault at the archaeological site of Qasr Tilah, Dead Sea Transform fault system, Jordan

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Abstract The archaeological site of Qasr Tilah, in the Wadi Araba, Jordan is located on the northern Wadi Araba fault segment of the Dead Sea Transform. The site contains a Roman-period fort, a late Byzantine–Early Umayyad birkeh (water reservoir) and aqueduct, and agricultural fields. The birkeh and aqueduct are left-laterally offset by coseismic slip across the northern Wadi Araba fault. Using paleoseismic and archaeological evidence collected from a trench excavated across the fault zone, we identified evidence for four ground-rupturing earthquakes. Radiocarbon dating from key stratigraphic horizons and relative dating using potsherds constrains the dates of the four earthquakes from the sixth to the nineteenth centuries. Individual earthquakes were dated to the seventh, ninth and eleventh centuries. The fault strand that slipped during the most recent event (MRE) extends to just below the modern ground surface and juxtaposes alluvial-fan sediments that lack in datable material with the modern ground surface, thus preventing us from dating the MRE except to constrain the event to post-eleventh century. These data suggest that the historical earthquakes of 634 or 659/660, 873, 1068, and 1546 probably ruptured this fault segment.

Key words archaeoseismology · Dead Sea Transform fault system · earthquake · Jordan · paleoseismology · Wadi Araba · cistern

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Introduction

Archaeological sites offer a unique opportunity to conduct paleoseismic investigations because they commonly contain a wealth of data related to the occurrence of major seismic events in the region. Buildings, artifacts, and pottery provide important age control for correlating the timing of multiple events. Most archaeological sites have been occupied for multiple periods of civilization and provide detailed information about the timing and occurrence of earthquakes. Ancient structures are commonly damaged by earthquakes, so repairs and reconstruction of collapsed structures can constrain the times of seismic events, whereas the collapse of structures provide data about the intensity of historical earthquakes. In rare cases, ancient structures were constructed directly overlying a fault and are offset by one or more historical earthquakes (Marco et al. 1997; Ellenblum et al.

1998; Niemi 2000; Klinger et al. 2000a; Meghraoui et al. 2003). Sites of this nature can potentially yield data about the magnitude and timing of multiple earthquakes at one location.

The Near East and eastern Mediterranean region is an ideal location to use archaeological sites to evaluate earthquake recurrence. Many ancient sites are located within 100 km of the Dead Sea Transform (DST) fault, a major strike–slip fault system that accommodates motion between the Sinai and the Arabian tectonic plates (Figure 1a). In addition to the long cultural history of the region, the arid environment and slow sedimentation rates leave archaeological structures remarkably well preserved and close to the surface, thus allowing detailed observation and relatively easy access to subsurface paleoseismic data.

The dates and occurrences of large (M>7.0) earthquakes in the eastern Mediterranean and Near East have been recorded in a variety of texts since the first Egyptian dynasty, providing a highly detailed catalog of major earthquakes. However, the combined effects of sparse habitation during periods of history, difficult traveling conditions, uneven population distribution, and an arid environment, probably result in historical accounts of earthquake extent, damage, and dates of occurrence that are somewhat biased. Earthquake

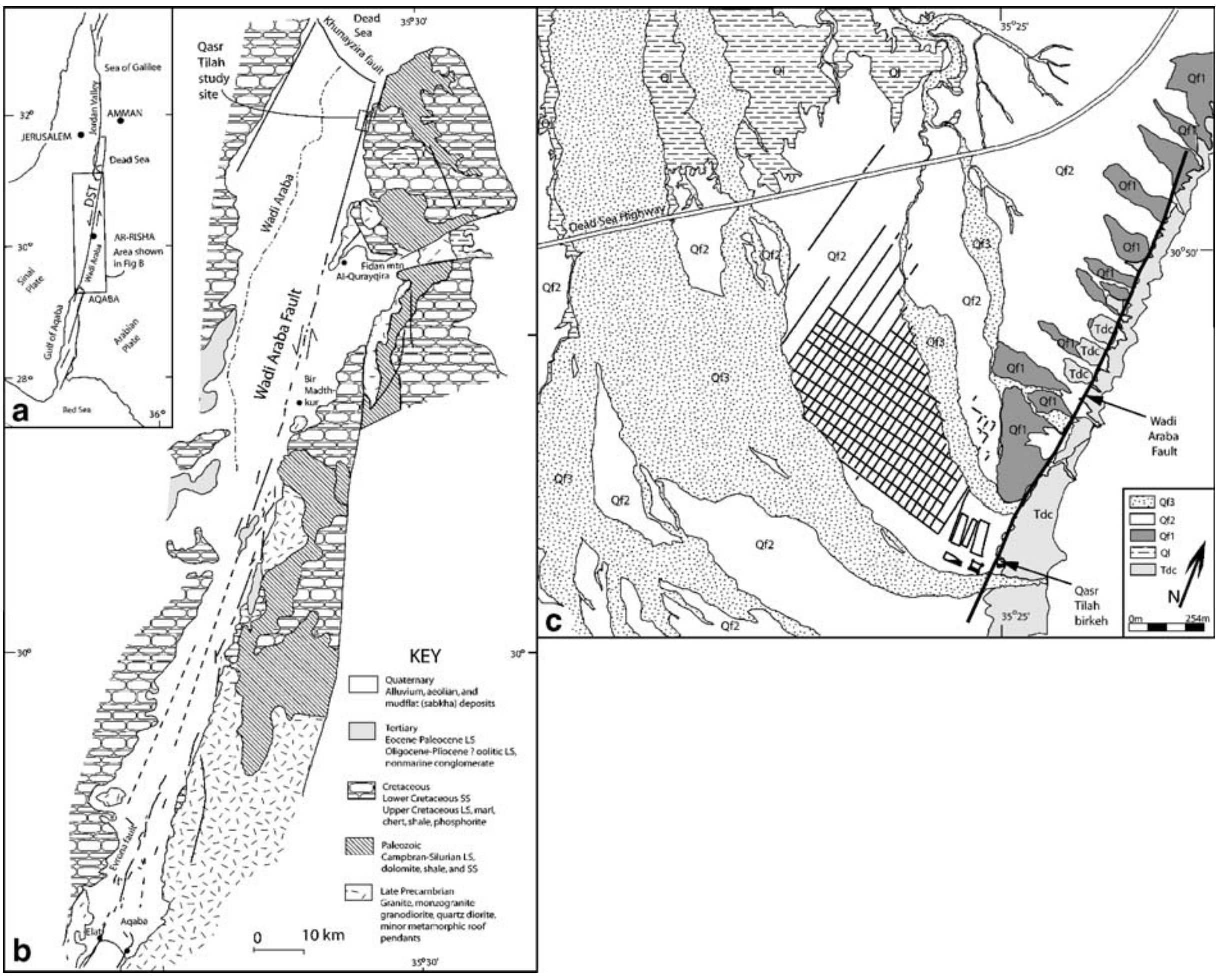

Figure 1 (a) Regional tectonic map of the Dead Sea transform fault system. (b) Schematic geologic map of the Wadi Araba valley showing study location (Modified after Garfunkel et al. 1981). (c) Schematic Quaternary geologic map of the study area (Modified after Zhang 1998). WAF is line trending N8°E. Qasr Tilah structures in SE corner of map as shaded polygons. Ancient agricultural fields represented as grid on Qf2 surface. Dead Sea Highway represented as double line in northern half of map. Tdc – Tertiary Dana Conglomerate bedrock units; Ql – Quaternary Lisan formation; Qf1 – oldest Quaternary alluvial-fan; Qf2 – Quaternary alluvial-fan overlying Qf1; Qf3 – most recent Quaternary alluvial-fan deposit.

catalogues therefore may only include reports of the largest seismic events. Furthermore, large earthquakes occurring closely in time can be reported as one earthquake, or conversely, a large, widely felt earthquake may be reported as two separate events.

This study focuses on archaeological and geologic evidence of past earthquakes at the archaeological site of Qasr Tilah located 30 km south of the Dead Sea in the Wadi Araba, Jordan (Figure 1b). The Wadi Araba is mostly unpopulated desert extending from the southern tip of the Dead Sea basin to the Gulf of Aqaba.

The Wadi Araba fault (WAF) is a fault segment of the DST that lies within the Wadi Araba valley. Fault segments of the DST have been the source of many historical large earthquakes; however, the epicenter and magnitude of these events are poorly constrained. In this paper, we describe archaeological and stratigraphic evidence of historical earthquakes at the ancient ruins of Qasr Tilah. By evaluating paleoseismic and archaeoseismic data, and correlating it with historical records, we can determine the rupture location of several historical earthquakes that have impacted the site.

Archaeological framework

The archaeological site of Qasr Tilah (Figure 2) consists of a fort (caravanseai), a water reservoir (birkeh or cistern), an aqueduct irrigation system and agricultural fields (Figure 2b). The birkeh is situated on an alluvial fan and appears to have been cut into the hill (Figure 2a). Two aqueducts that originate in the adjacent Wadi Tilah feed the birkeh at the southeast corner and in the middle of the east wall. The south wall has a channel along the top that exits into a settling pool located at the southwest corner of the birkeh. A short, NW-trending aqueduct connects the settling pool at the base of the birkeh with a W-trending aqueduct that appears to extend to the field system (Figure 2a).

Previous archaeological surveys at Qasr Tilah were conducted by Musil (1908), Frank (1934), Glueck (1935), Raikes (1985), MacDonald (1992), Niemi (2000), and Niemi and Atallah (2000). Glueck's (1935) site drawing indicates that an aqueduct connected a spring in Wadi Tilah to the birkeh. He described the birkeh as having a set of steps into it at the southeast corner, and an aqueduct extending from the center of the western reservoir wall. However, due to vandalism and weathering of the site, the connection of the W-trending aqueduct with the birkeh is now unclear. The W-trending aqueduct appears to have been constructed above ground and is preserved along parts of its length, albeit unexcavated. No mention of the short NW-trending aqueduct excavated in this study exists in the previous literature.

The structures at the site differ in the quality of their preservation and age. The fort, believed to be the Roman fort of *Toloha* mentioned in the fourth century *Notitia Dignitatum* (Seeck 1876; Glueck 1935; Frank 1934; Raikes 1985), is largely in ruins with its walls and corner towers reduced to piles of boulders and cobbles. The aqueducts in Wadi Tilah are built into the wadi walls and are intact in several locations where they have not yet eroded or collapsed.

Movement on the WAF has laterally offset the birkeh and the NW-trending aqueduct during several earthquakes (Figure 2c). The northwest corner of the western wall of the birkeh has a large crack with a left-lateral offset of 1.5–2 m (Galli 1997, 1999) indicative of faulting during earthquake rupture (Galli 1997, 1999; Niemi 2000; Niemi and Atallah 2000; Klinger et al. 2000a; Galli and Galadini 2001). The birkeh is generally intact elsewhere with the exception of large fissures and cracks at the northwest corner and fractures along the western wall.

Prior to research conducted as part of the Wadi Araba Earthquake Project (Niemi 2000, 2002), detailed archaeological excavations had not been conducted at Qasr Tilah.

Previous investigations consisted of a pottery survey and the study and description of above ground structures. Musil (1908), Frank (1934), Glueck (1935), and MacDonald (1992) documented Qasr Tilah as a Nabataean and Roman settlement based on abundant surface sherds in the area. MacDonald (1992) also collected some Byzantine and Umayyad surface potsherds at the site and documented ruins of Byzantine houses (village) along the fan surface of Wadi Tilah. Galli (1997, 1999) and Galli and Galadini (2001) attributed the extant birkeh to the Nabataean–Roman period, based on the available archaeological literature (Khouri 1988). It will be demonstrated, however, that the age is different from that supposed. See Table 1 for a chronology of archaeological periods in Jordan.

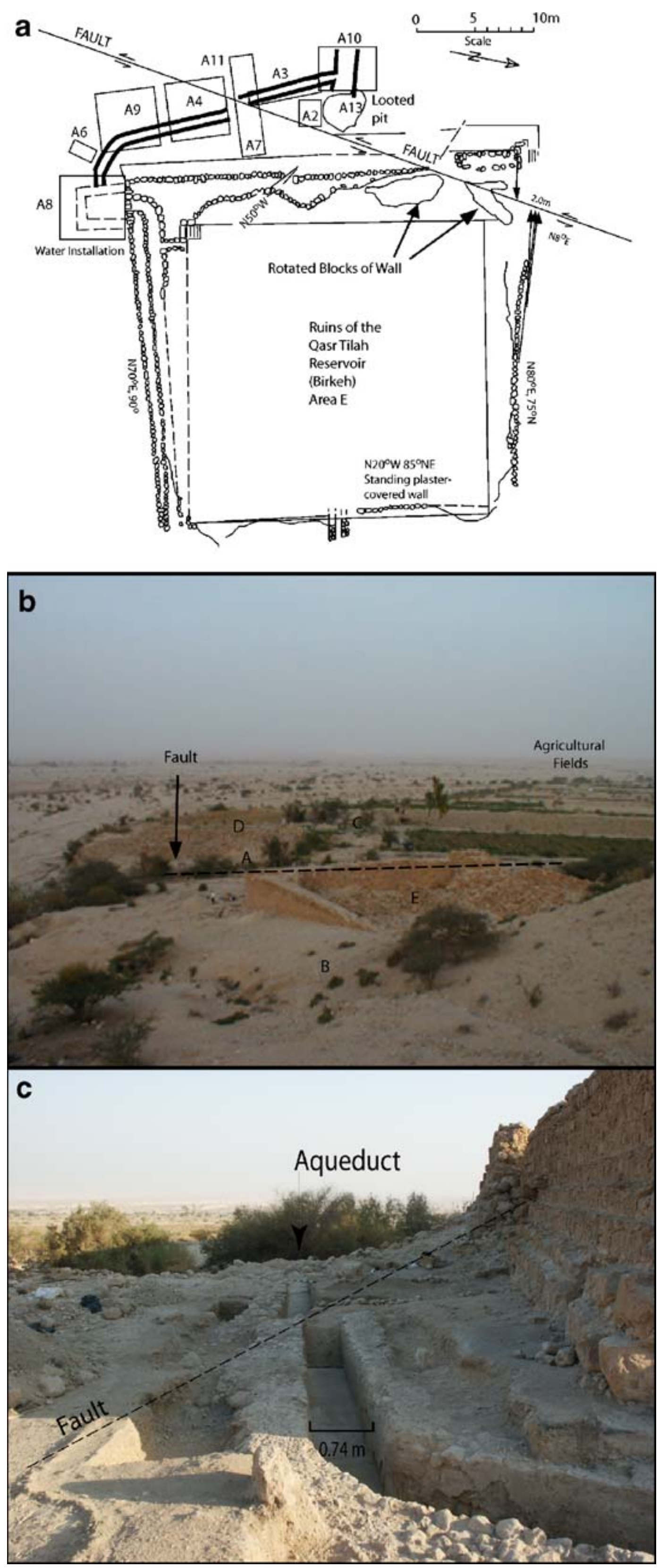

Figure 2 (a) Site map of Qasr Tilah water structure (birkeh) and aqueduct with archaeological trenches of area A. WAF is the line trending N8°E. Trench A.7 encompasses offset aqueduct. (b) Birdseye view of the study area to west. Area A is located on west side of the birkeh. Area B (influent aqueduct) is in the foreground, area C is the west trending aqueduct; area D is the Roman period fort, and area E is the interior of the aqueduct. Ancient and modern agricultural fields are in the background. (c) Rupture of the west birkeh wall and aqueduct. Aqueduct channel is 0.74 m wide for scale.

Table 1 Historical chronology of Jordan from 1st century B.C. to present (Modified after Stager et al. 2000)

Civilization	Time period
Nabataean	312 B.C.–106 A.D.
Roman	63 B.C.–324 A.D.
Early Roman (63 B.C.–106 A.D.)	
Late Roman (106 A.D.–324 A.D.)	
Byzantine	324–636
Early Byzantine (324–491)	
Late Byzantine (491–636)	
Arab conquest	636–661
Umayyad	661–750
Abbasid	750–969
Fatimid	969–1099
Crusaders	1099–1187
Ayyudid	1173–1260
Mamluk	1260–1515
Ottoman	1515–1918
Modern	1918–present

Tectonic setting

The Wadi Araba fault (WAF), also called the Arava fault, is the southern segment of the Dead Sea Transform (DST) fault system. This fault system is part of the major left-lateral, strike–slip, plate boundary that separates the Arabian and Sinai plates (Figure 1a). The DST extends for approximately 1,000 km and in the north terminates at the Taurus–Zagros collision zone and in the south at the Red Sea spreading center. The fault has an average trend of N15°E and a cumulative post-Miocene displacement of 107 km based on offset volcanic rocks (e.g., Freund et al. 1970; Garfunkel et al. 1981). The Wadi Araba extends 160 km from the Gulf of Aqaba in the south to the Khunayzira (Amazyahu) fault at the southern end of the Dead Sea basin (Figure 1b).

The DST formed from the rifting and subsequent separation of Africa and Arabia approximately 25–30 Ma (McKenzie et al. 1970). Initial deformation along the DST began with the formation of the Syrian Arc in Late Cretaceous and early Tertiary time, and is now expressed as fold belts extending from Sinai to Syria (Syrian Arc). Extension along the African–Arabian plate boundary is accommodated by rifting in the Red Sea and the Gulf of Suez, while transtension between the plates is accommodated along the DST (Garfunkel et al. 1981).

The WAF fault trace is expressed as small transpressional structures at right jogs and transtensional structures at left jogs as it crosses the valley floor. Offset streams and shutter ridges mark the fault trace as it skirts the mountains composed of Tertiary and Mesozoic rocks on the east edge of the valley (Atallah 2002) (Figure 1c). Late Quaternary measurements of laterally offset geomorphic features are laterally offset 1–20 m, which yields a Holocene slip rate of 4.7± 1.3 mm/year (Zhang 1998; Klinger 1999; Klinger et al. 2000a, b; Niemi et al. 2001).

Modern microseismicity along the Wadi Araba fault is low (GII 2005). Two large earthquakes have occurred on the southern DST since 1900, but neither was located along the WAF. A large (M7.3) earthquake occurred on July 1, 1927 (Ambraseys et al. 1994) in the Dead Sea (Shapira et al. 1993; Niemi and Ben-Avraham 1994), and Aqaba was damaged by a M7.2 earthquake on November 22, 1995, which was located offshore in the Gulf of Aqaba (Shamir 1996).

Field investigations

As part of the ongoing Wadi Araba Earthquake Project, we collected field data in 2002 and 2003 and incorporated data from 1999 and 2000 field seasons. Our archaeological excavations focused on exposing the aqueduct and its association with other structures at the site (Figure 2c). We surveyed the excavated archaeological structures using a Total Station (Figure 3a; Figure 4). We also excavated a series of exploratory trenches (Figure 2a) along the length of the NW-trending aqueduct, and archaeoseismic data from Trench A.7, including descriptions of the stratigraphy, evidence of faulting, and paleoseismic features. Trench A.7 is a 2 m wide (N–S), 7 m long (E–W), and 2.5 m deep hand-excavated pit that encompassed the aqueduct and the sediments between the aqueduct and the wall of the birkeh. The east end of the trench abuts the birkeh.

Radiocarbon dating of charcoal samples from significant subsurface horizons provides age control that is summarized in Table 2. Pottery sherds and artifacts provided age control by relative typological dating, which is based on identifying ‘diagnostic’ sherds or artifacts that indicate the form of a vessel that the sherd came from (e.g., a rim or jug handle), and assigning it to a point of origin and the civilization,

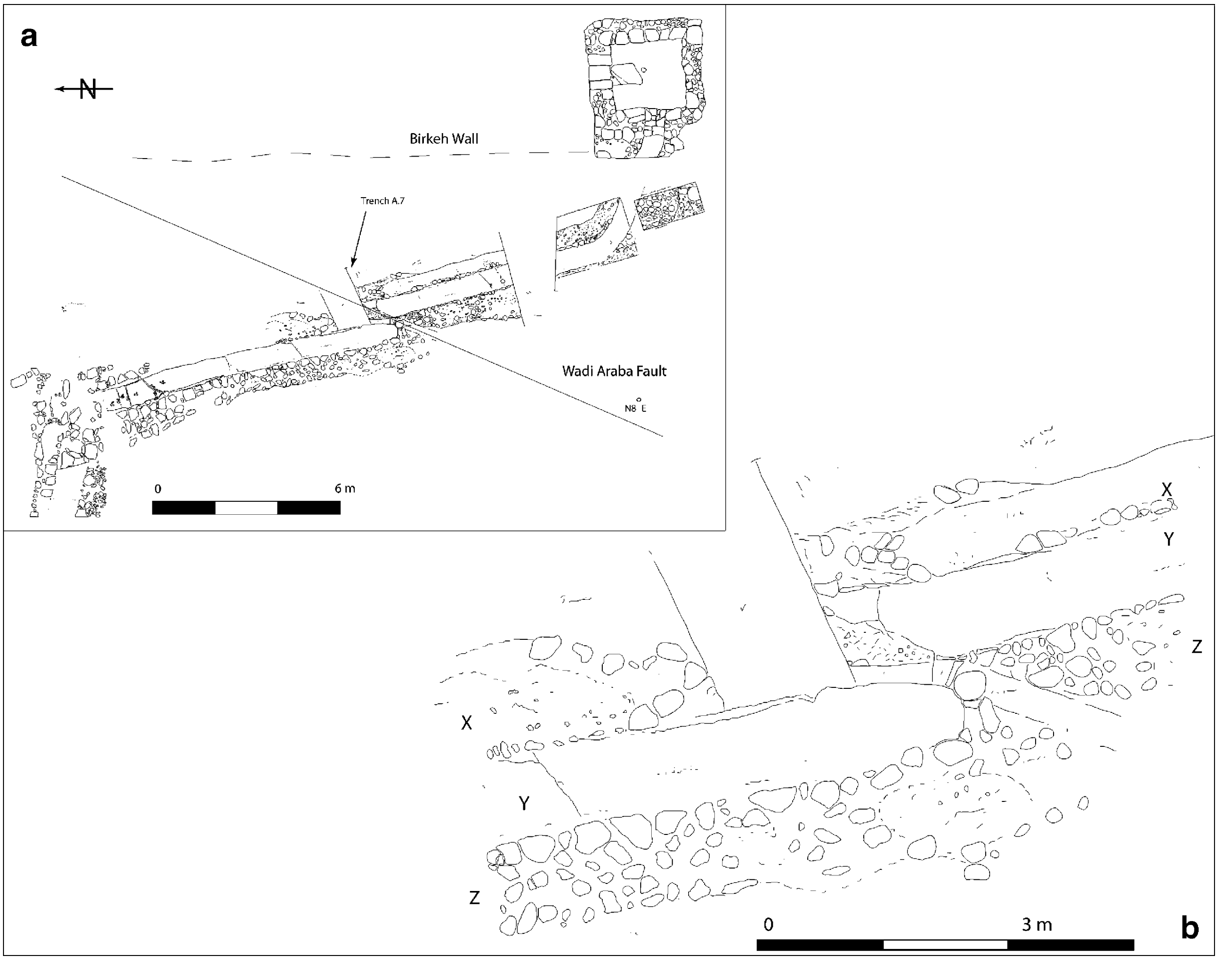

Figure 3 (a) NW-trending aqueduct and settling pool from Total Station survey data. Unexposed sections of the aqueduct are unexcavated trench boundaries (balks). The junction of the NW aqueduct with the west trending aqueduct is located at the lower left corner. The dashed line indicates approximate location of the west birkeh wall. (b) Offset of aqueduct in Trench A.7 and vicinity. X: east aqueduct wall; Y: aqueduct floor; Z: west aqueduct wall. Offset measurements taken in the field and digitally from five locations along the aqueduct walls and floor along the trend of the fault (N8°E).

and the time period when the sherd or artifact was used based on stylistic differences between different cultures.

By its very nature, excavation destroys the stratigraphic relationships of the artifacts and structures being articulated. In an effort to preserve these relationships, detailed section drawings of the trench walls and plan views of the horizontal extent of excavation (top plan) are drawn daily, revised, and updated using a line level datum and grid. These drawings record horizontal and vertical placement of artifacts in the trench and serve as a snapshot of excavation progress. Each balk, or trench wall, in Trench A.7 was digitally photographed on a 0.5 by 1.0 m grid and compiled as a photomosaic. Our excavations at Qasr Tilah followed archaeological methods (Rapp and Hill 1998), and each trench was located based on the possibility of exposing significant information about the site.

Each stratigraphic horizon or zone of interest is designated as a locus and is qualitatively described and recorded. We describe and interpret the physical properties (grain size, compaction, color, and artifact content), architectural significance, and spatial relationships with other loci in a daily excavation progress logbook.

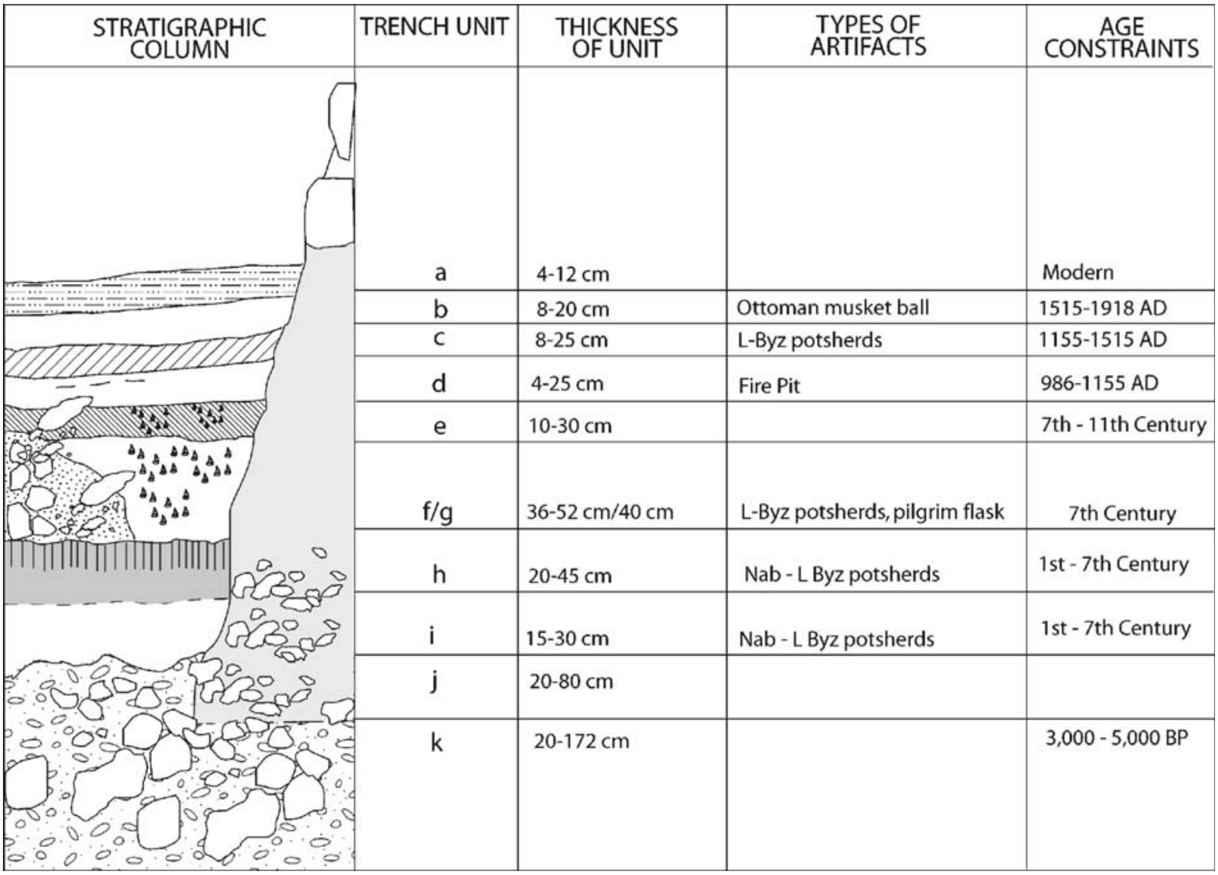

Figure 4 Schematic stratigraphic column of Trench A.7. Thicknesses of units are generalized from measurements of unit throughout the trench. Listed artifacts provide age control for constraining deposition and earthquake history in units where they were discovered. Age constraints come from radiocarbon data and typological dating of sherds.

Trench stratigraphy

The Qasr Tilah site is built on late Quaternary alluvial-fan sediments. These alluvial-fan deposits, divided by Zhang (1998) into three units (Q_{f1}, $Q_{f2,}$ and Q_{f3}), all post-date the lacustrine deposits of the Lisan Formation (>15 ka). The archaeological ruins of Qasr Tilah were constructed in Q_{f2} deposits, and the braided stream deposits of Q_{f3} accumulated after construction of the site. The agricultural fields, site

Table 2 Radiocarbon data

Sample name	Material	Source unit	d^{13}C	^{14}C age	±	2-σ calibrated calendar age A.D.	
QT03-4[a]	Charcoal in mortar	Birkeh arch	−25	1410	40	689	566
QT03-6[a]	Charcoal in mortar	Standing wall – B.5.9	−25	1380	40	721	603
A7.C3.N[b]	Charcoal	Unit d	−23.9	990	40	1155	986

The samples were prepares and analyzed at Lawrence Livermore National Laboratory by AMS. The results were reported in September 2003. The resulting radiocarbon age for each result was given a 2-σ calibrated calendar date using the Calib5.0.1 program (Stuiver and Reimer 1993).

[a] Calibrated by Calib5.0.1 (Stuiver and Reimer 2003)

[b] Calibrated by Lawrence Livermore National Laboratory

TRENCH UNIT	CONTACT	LITHOLOGY
a	Gradational	Silt, with angular pebbles, roots, well sorted, fine bedding, erosional contact, 10YR 6/4, light yellowish brown, loose compaction, modern ground surface, caps MRE
b	Gradational	Silt, some cobbles, well sorted, fine bedding, erosional contact, 2.5Y 7/4, pale yellow, loose compaction
c	Erosional	Silt and gravel, well sorted, fine bedding, erosional contact, 10YR 7/3, very pale brown, loose compaction
d	Erosional	Silt, some sand and very small pebbles, *turitella*, pottery, mortar pieces, pale yellow, 2.5Y7/4. Very fine horizontal bedding with some cross-bedding on east side of bottom contact, charcoal layer approximately 1m across on top of rock at bottom of bed, copper item (coin?) located in the charcoal, caps event II (penultimate event).
e	Sharp	Silt, some angular gravel, some sand, *turitella*, small bits of mortar, light compaction, some pottery (Nab & E-Byz), pale yellow, 2.5Y 7/3, no distinct bedding pattern, caps event III
f/g	Sharp	Silt, some angular gravel and large mortar covered cobbles, 2.5Y 7/3 Silt, some rounded rounded and angular cobbles, *turitella*, some pottery, firm compaction, pale yellow, 2.5Y 8/2, caps Event IV
h	Gradational	Silt, some subround and subangular pebbles, pottery, firmly compacted, very pale brown, 10YR 7/3
i	Sharp	Pebbles, subrounded and bladed and finely bedded silt, grading to pebbles and sand, very pale brown to pale yellow, 10YR 7/4
j	Sharp	Calcrete - pebbles and coarse sand, some subrounded cobbles, sand cemented to pebbles and cobbles, grain-supported, poorly sorted, cemented, 2.5Y 7/1, light gray
k		Pebbles and coarse sand, some subrounded cobbles, sand cemented to pebbles and cobbles, grain-supported, poorly sorted, loose, yellow, Q_{f2} alluvial fan deposits

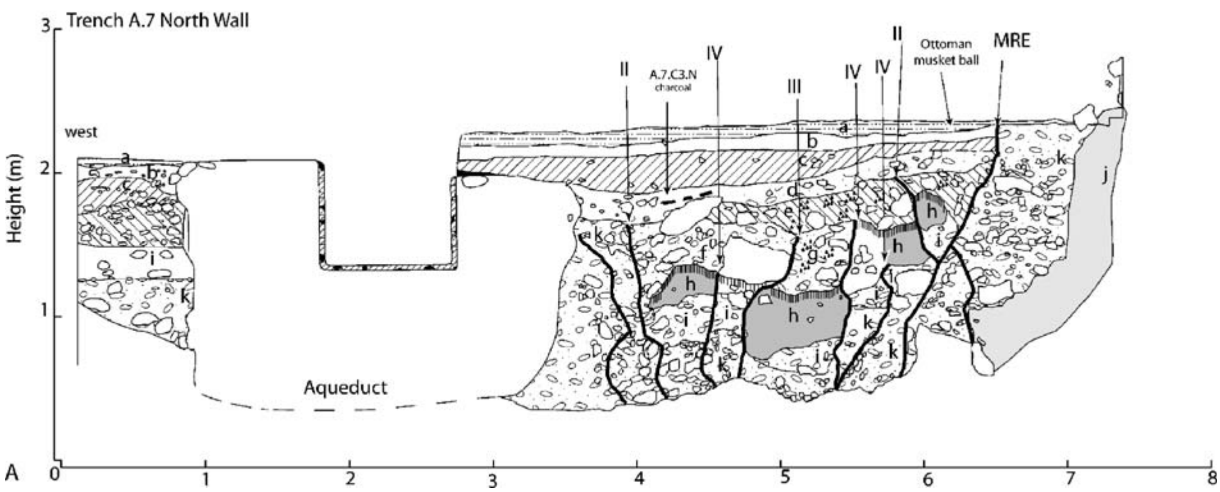

Figure 5 Schematic diagram of Trench A.7 north wall. Stratigraphic units are identified by lowercase letters. Faults are emphasized by heavy lines. Earthquakes are identified by Roman numerals, with IV as the oldest. Dashed lines indicate unexcavated portion of aqueduct floor.

architecture, and the post-occupational natural deposits are designated Q_{ar} because human settlement influences sedimentation processes (Figure 1c).

The sediments exposed in Trench A.7 are composed entirely of Q_{f3} and Q_{ar} deposits, excavation terminated in the top of the Q_{f2} alluvial-fan sediments. We identified nine distinct stratigraphic layers in the Q_{ar} deposits (Figure 4). Figure 5 shows lithologic descriptions of each layer. Three horizons (h, i, j) are associated with construction/reconstruction (*terminus ante quem*) and occupation of the site. Two deposits (f, g) result from the disruption and collapse of the birkeh and aqueduct. Five layers are related to post-collapse deposition after site abandonment to the present (a, b, c, d, e). As shown on the trench logs, thinly bedded deposits dominate the stratigraphy at Qasr Tilah. One thousand four hundred years of history are recorded in the approximately 1.5 m of strata from the time of occupation to modern times.

We identified evidence of past earthquakes in the trench walls based on offset stratigraphic horizons, upward terminations of faults, fissure fills, and outward-splaying faults (flower structures). Faulting opened fissures at the ground surface at the time of an earthquake, which filled with mixture of near-surface sediments. Faulting also juxtaposes Q_{f2} alluvial-fan sediments against younger Q_{f3} sediments. Eight fault strands cut through all but the uppermost layer vertically in apparent dip–slip or oblique-slip motion. Vertical offset or subsidence of the older units created

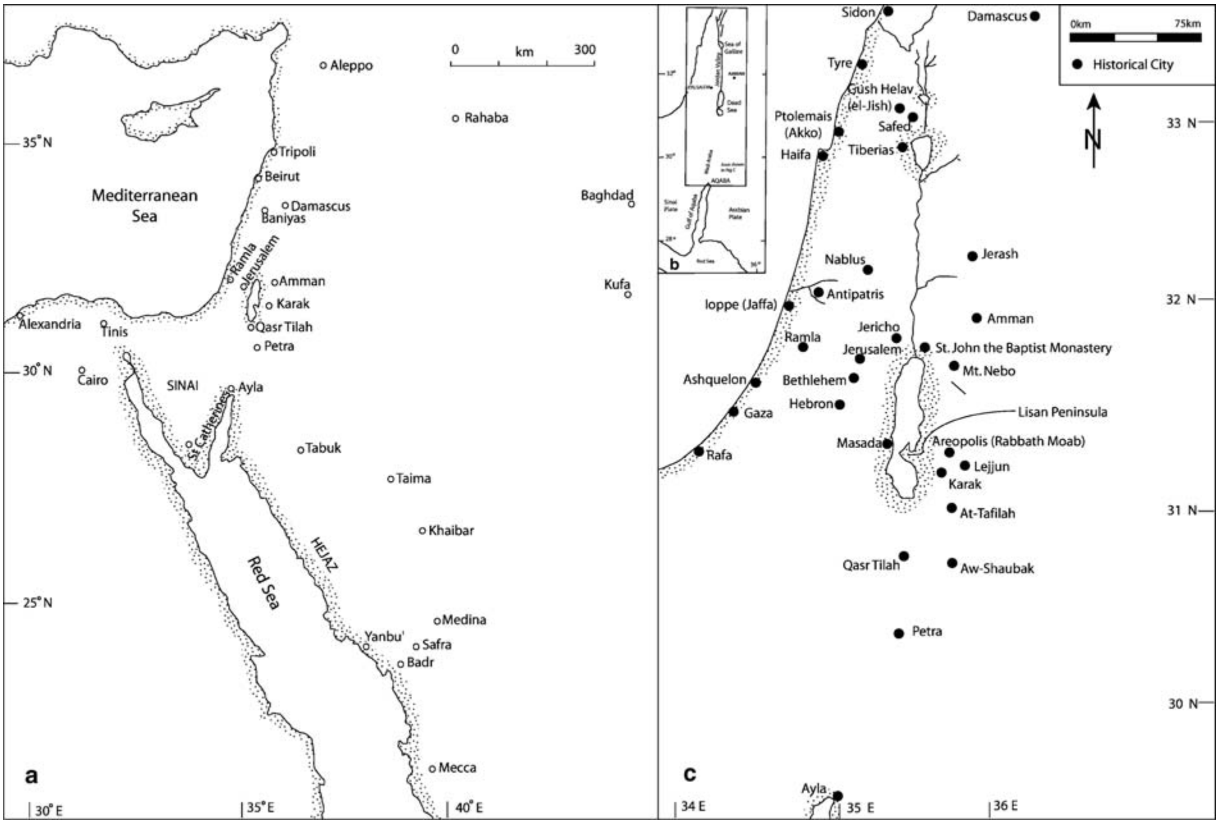

Figure 6 (a) Regional historical seismicity map showing area and historical cities of eastern Mediterranean and Near East areas affected by earthquakes from the 6th century to the present (Modified after Ambraseys et al. 1994). (b) Regional context map (Modified after Garfunkel et al. 1981). (c) Historical geographical map showing cities with reported historical damage from earthquakes from 4th to 18th century Palestine (present day Israel and Jordan) (Modified after Russell 1985).

a depression or trough between the aqueduct and the birkeh wall, which filled with younger sediments and raised the ground surface back to level.

Unit j is a ‘calcrete’ layer formed in the fan sediments of Q_{f2} (unit k). Unit k is composed of loosely packed, subrounded to rounded, sand, cobbles and pebbles that is clast-supported, and has no apparent bedding. Unit j underlies the birkeh and is identical to unit k in grain size, matrix and bedding patterns, with no apparent discontinuity between the units. However, the clasts are cemented together by plaster that leached from the birkeh into underlying sediments, which suggests that unit j formed in situ in unit k. The chemical composition of the ‘calcrete’ has not yet been analyzed.

Two horizons (units h and i) overlying unit k are the occupational horizons during construction and operation of the aqueduct and birkeh. The distinct, though poorly developed horizon is marked by a firmly compacted silt layer, which grades downward to pebbles, and abundant pottery. Potsherds from the top of unit h range from Nabataean (312 B.C.–106 A.D.) to Late Byzantine/early Umayyad (324–636 A.D. to 661–750 A.D.) cultures, indicating occupation since at least the first century A.D., the latest date of Nabataean occupation (*terminus ante quem*). Diagnostic pottery (pottery with a rim, handle or some other identifying feature) from the late Byzantine–early Umayyad period (fifth to seventh century) includes a pilgrim’s flask along with assorted sherds with rims and handles. The age of the pottery, coupled with the radiocarbon dates of sixth to seventh century from the birkeh wall (Niemi et al. 2001) suggest that this was the ground surface during the construction/reconstruction phase of occupation.

Unit g is composed of poorly sorted, matrix-supported silt and subrounded mortar-covered cob-

bles. The matrix-supported, poorly sorted character of this unit suggests that it was deposited rapidly without time to settle. *Turitella*, a still-water gastropod, is present in unit g, which suggests that the water responsible for deposition came from inside the birkeh rather than from the flowing water of the aqueduct, which is supported by similarities between unit g and sediment sampled from inside the birkeh in color, grain size, and texture. *Turitella* are present in both layers. The presence of mortar-covered rocks that were originally part of the aqueduct in unit g caused a damming effect and water that came from the north pooled in a depression at the now-offset aqueduct.

The large concentration of mortar-covered cobbles and boulders in unit f is interpreted to be sediments derived from rupture of the aqueduct. Unit f is clast-supported with fine silt, pebbles, and potsherds filling the interstices between the mortar-covered cobbles. Aqueduct construction stones are located primarily in unit f indicated by two large mortar-covered boulders and smaller cobbles. Some mortar cobbles from the aqueduct are in overlying layers; however, these cobbles have been reworked and redeposited after the rupture of the aqueduct. Both units f and g were deposited simultaneously, based on their adjacent rather than horizontal positions, originating in opposite directions and converging near the tumble of the aqueduct, where a small basin formed due to coseismic subsidence.

Unit e was deposited after the rupture and collapse of the birkeh and aqueduct. Unit e is similar to grain size and color to unit f, however, there are few large clasts, and its fine bedding indicates that it accumulated slowly rather than instantaneously from an earthquake.

Unit d is loosely compacted, finely bedded silt, fine sand and small pebbles that is capped by a layer of charcoal from a fire. Radiocarbon dating of the charcoal yielded a calibrated calendar date of 986–1155 A.D. (Table 2). We found a flat copper object, possibly a coin, at the top of this layer but, no date has been assigned to it, along with Nabataean to Umayyad pottery in this horizon. *Turitella* shells are present throughout the layer, indicating a still-water depositional environment, which suggests that a water-filled depression was located between the aqueduct and birkeh. However, the loose compaction of the layer along with the very fine bedding suggest that the layer may have been deposited by wind, rather than with the *turitella* being reworked from earlier deposits.

Units a, b, and c, which overlie unit d, are composed of finely bedded, loosely compacted sandy silt. They are differentiated by slight variations in color and grain size and have distinct bedding contacts. Potsherds ranging from Nabataean to Late Byzantine cultures are present in the units. We cannot assign an age to units b and c because they lack artifacts or datable organic material. However, we found an Ottoman age musket ball at the base of unit a (modern ground surface), thus dating the bottom of unit a to a maximum age of 1515 A.D., the earliest date of Ottoman occupation of Palestine (Table 1). The age constraint of units a and d bracket the ages of units b and c from 1155, the most recent radiocarbon age of the charcoal, to 1918 A.D., the date of the end of the Ottoman occupation. We cannot determine the age of the contact between units b and c.

Archaeological evidence

Evidence of seismic rupture is most obvious in the left-lateral offset of the northwestern corner of the birkeh and the aqueduct (Figure 2). The fault trace strikes N8°E and offsets the birkeh wall 2.2±0.5 m (Klinger et al. 2000a). A repair to the northwest corner of the birkeh wall suggests that an earthquake damaged the birkeh shortly after it was constructed (Niemi and Atallah 2000). The birkeh wall was built directly over the fault, and an additional course of stone was added to the top of the wall and coated in plaster following subsidence of the northwest corner. Based on the vertical or oblique slip we observed in unit h, the occupational ground surface, the ground surface subsided relative to the easternmost edge of Trench A.7 (Figure 5). These data support the observation that the northwest corner of the birkeh wall subsided during an earthquake prior to the repair. Niemi (2000) dated charcoal in the mortar of the birkeh to be 641–687 A.D., which agrees with dates determined from other workers (558–776 A.D. in Klinger et al. 2000a). The radiocarbon date defines a *terminus ante quem* for the construction of the birkeh since the sampled charcoal could reflect repairs, reconstructions or other surficial modifications. For the purpose of this paper, this *terminus ante quem* limit will be referred to as the date of construction. A

radiocarbon date from plaster on the top of the repaired course of stone agrees with the radiocarbon date from plaster on the lower wall (Niemi and Atallah 2000). The similarity in calendar ages of the repaired corner and the lower wall suggests that the birkeh wall sustained damage, and was repaired shortly after the extant birkeh was constructed, or reconstructed over an earlier structure.

Radiocarbon dates on charcoal in mortar from the east–west trending aqueduct located between the fort and the birkeh, and an arch located in the west wall of the birkeh have a similar age: the birkeh archway has a calendar date of 566–689 A.D., and the aqueduct has a calendar date of 603–721 A.D. (Table 2). These dates confirm close construction ages of the aqueduct system with the birkeh.

The aqueduct is laterally offset, 1.6±0.4 m (Figure 3b). We exposed the base and foundation of the aqueduct in order to determine the manner in which the structures were constructed. Based on the lack of facing stones or plaster on the exterior walls of the aqueduct, the aqueduct appears to have been constructed below ground in the sediments of unit h by pouring mortar and stones into a trench rather than as a freestanding structure.

We did not identify any pottery younger than Late Byzantine–early Umayyad cultures (fifth to seventh century) in our excavations. Unit h, the occupational surface, contains a large amount of Late Byzantine–early Umayyad potsherds including diagnostic pieces of a pilgrim's flask. Unit h is buried by units f and g, both of which contain rubble from the collapsed aqueduct and the ruptured birkeh wall. A mixture of Nabataean to Early Umayyad potsherds were collected from the overlying layers. However, the pottery was deposited in younger layers as a result of reworking of older deposits by wind, water anthropogenic activities. In addition, Late Byzantine–early Umayyad potsherds were collected from the interior fill of the aqueduct, which suggests that the aqueduct was out of use and had filled with sediment after the seventh century. The lack of pottery younger than Late Byzantine–early Umayyad cultures coupled with radiocarbon data from the tenth to twelfth centuries (unit d) the collapsed aqueduct and associated deposits (units f and g), which overlies the occupation surface unit h, suggests that the site was abandoned some time in the seventh century.

Chronology of faulting

The Wadi Araba fault crosses Trench A.7 between the aqueduct and birkeh in a 3.5 m wide zone (Figure 6). Coseismic subsidence along the fault trace formed a depression that contains datable deposits. We identified stratigraphic evidence of four earthquakes in the trench. Archaeological evidence coupled with paleoseismic evidence indicates that four earthquakes likely occurred between the seventh century and 1918 A.D. Figure 5 shows the age boundaries of each unit in the trench, and the respective artifacts or stratigraphic data supporting the unit's age.

The fault strand that moved during the most recent event (MRE) terminates 2–4 cm below the surface and juxtaposes unit j and younger stratigraphic layers (Figure 5). This fault strand is capped by unit a, the modern ground surface. A definite date cannot be assigned to this event because any stratigraphic units that may have originally buried unit j were eroded prior to the deposition of unit a. However, an Ottoman period musket ball near the base of unit a establishes the minimum date for the MRE is pre-1918, the end of Ottoman occupation of the region. The maximum age for the MRE is 1515, the beginning of Ottoman occupation, based on the truncation of layer b, which, by virtue of the musket ball in unit a, is older than 1515–1918.

The penultimate event (II) offsets units e, f, and g and the underlying layers. Unit i is present at the top of and in the mixed sediments of a flower structure, which marks the ground rupture of the earthquake. Below unit e, fragments of units e, h, i, j, and k are mixed in the fissure fill. The fault terminates at the top of unit e, which indicates that unit e was the ground surface at the time of the earthquake. Unit e is capped by the undeformed unit d, which, due to its radiocarbon date of 986–1155 A.D. (Figure 5), limits the minimum date for event II to the twelfth century. The maximum date for event II is post seventh century abandonment of the site in underlying layers.

The antepenultimate event (III) is marked by the rupture trace being buried by unit e. Units f, g, h, i, and k are offset. Fault terminations at the top of units f and g suggest that this was the ground surface at the time of event III, and therefore, it also occurred after the seventh century. The minimum date for event III cannot be earlier than the basal age of unit d (986–1155 A.D.).

The earliest event documented in this study (Event IV) occurred during repair and reconstruction of the birkeh and aqueduct. Evidence for this event is the displacement of units h, and i, the occupational surface at the time of use of the structures, and k. Event IV is capped by units f and g, which represent the rupture of the aqueduct and birkeh. Because pottery younger than late Byzantine–early Umayyad cultures is not present at the site, it is likely that the stratigraphic evidence for the event IV earthquake occurred in the seventh century. Furthermore, dating of the charcoal from the birkeh repair firmly places this earthquake in the seventh century.

Discussion

Because the eastern Mediterranean was a focal point of continental and marine trade and migration throughout human history, the region is a unique resource for studying historical earthquakes. Written records of earthquakes date back to the First Dynasty in Egypt in 3100 B.C. (Ambraseys et al. 1994) and have been collected by various sources and civilizations since.

Modern earthquake catalogs contain information from historic sources. Earthquake accounts and descriptions before 1900 are from medieval Arabic texts, Byzantine, Syriac, and Amharic histories, and European travel literature and technical studies. The main source for post-1900 data is seismological records from seismograph stations and other instruments.

Assuring a reliable description of an historical earthquake requires critical assessment of historical records. Detailed accounts of earthquakes come from a variety of sources; however, primary texts are rarely available to develop modern earthquake catalogs. The majority of historical data used to document pre-instrumental earthquakes comes from secondary or tertiary accounts, thus introducing the possibility of distortion or error during translation and transcription between the texts. For pre-instrumental earthquakes, the epicentral location is based on reports of the felt area, but inaccuracies due to uneven population distribution over the felt area and poor communication and written documentation can bias accounts of damage and other details of the earthquake (Ambraseys et al. 1994). Because of the harsh, arid climate and the rugged terrain of the Middle East, population centers are mainly located on the Mediterranean coast, Red Sea coast or along the Jordan River/Dead Sea Basin. Accounts of earthquakes felt in the sparsely populated eastern deserts were commonly delayed, sometimes for many years, before being added to historical records. Furthermore, small events may have been unnoticed and not recorded. These factors result in an incomplete record of $M<7.0$ earthquakes, and a record that favors large ($M>7.0$) earthquakes (Ambraseys et al. 1994).

Interpretation of historical earthquake information includes gathering data to define the epicentral location and the maximum intensities. Damage reports in cities affected by an earthquake provide an estimate of the area of land in which the earthquake was felt (radii of perceptibility). Magnitude is estimated by correlating the historical location and felt area data with twentieth century earthquakes (Ambraseys et al. 1994).

Recent earthquake catalogs indicate that major earthquakes were felt in the Wadi Araba and/or the Dead Sea area in A.D. 362, 363, 372, 419, 551, 634, 659/660, 672, 746, 747, 748, 749, 859, 1032, 1033, 1063, 1068, 1070, 1202, 1211, 1212, 1261, 1273, 1293, 1312, 1456, 1458, 1546, 1588, 1834, 1837. However, this list seriously overestimates the number of earthquakes in the area because many dates may refer to the same event. Errors in translation of the original texts coupled with errors in converting dates to the modern calendar contribute to confusion and disagreement on the dates of various earthquakes. Additional errors in recent earthquake catalogs stem from repeating inaccurate dates and earthquake descriptions reported in earlier works (Poirier and Taher 1980; Sieberg 1932).

For the purpose of this historical earthquake review, we evaluated the major recent historical catalogs and compared the event dates. Because of conflicts regarding the dates of key events, we evaluated the supporting data for each event and determined a best-supported date. Table 3 summarizes the regional earthquake catalogs from Russell (1980, 1985), Ambraseys et al. (1994), Amiran et al. (1994), Ben-Menahem (1991), Guidoboni et al. (1994), and Guidoboni and Comastri (2005) for post-sixth century earthquakes that likely affected the Wadi Araba and Dead Sea area. Locations of historical cities are depicted in the regional seismicity maps in Figure 6.

The earthquake intensity data suggest that major post sixth century earthquakes probably occurred in the Wadi Araba and Dead Sea fault in 634, 659/660, 873, 1068, 1212, 1293, 1458, 1546, and 1588 (Ambraseys et al. 1994; Amiran et al. 1994; Ben-Menahem 1991;

Table 3 Summary of historic earthquakes, the respective source area location and damage reports from historical accounts in the Dead Sea/Wadi Araba region from the 6th century to the present

Date	Catalog	Location	Damage
551	Ambraseys et al. (1994); Amiran et al. (1994); Guidoboni et al. (1994); Russell (1985)	Dead Sea	Severe damage to Beirut, Jerusalem, Tripoli, Tyre, Sidon, Jerash, Mt Nebo, el-Lejjun, Petra destroyed and abandoned
634	Guidoboni et al.(1994); Russell (1985)	Dead Sea	Thirty days of aftershocks followed this earthquake. Archaeological excavations indicate damage at Beth-Shan.
659/ 660	Amiran et al. (1994); Guidoboni et al. (1994); Russell (1985)	Dead Sea	Strong earthquake in Jericho and Jordan valley; Monasteries of St. Euthymius and St. John the Baptist destroyed.
873	Ambraseys et al (1994)	Wadi Araba/ Arabian Desert	Bedouin tribes fled to Mecca for shelter from region around Medina and Taima.
1068	Ambraseys et al. (1994); Amiran et al. (1994); Guidoboni and Comastri (2005)	Wadi Araba	Two events in 1068 (Guidoboni and Comastri 2005). This entry discusses the 18 March earthquake. Major damage from Israel to Hejaz. Damage in Tinnis and Alexandria. Aila completely destroyed, and all inhabitants were killed. Castle at Karak destroyed.
1212	Ambraseys et al. (1994); Amiran et al. (1994); Guidoboni and Comastri (2005)	Wadi Araba/ Gulf of Aqaba	Severe damage at Aila. Towers and houses in Wadi Araba destroyed. Citadel towers collapsed and many deaths in Shawbak and Karak. Cairo damaged, and St. Catherine monastery in Sinai destroyed.
1293	Ambraseys et al. (1994); Amiran et al. (1994); Guidoboni and Comastri (2005)	Dead Sea/ Wadi Araba	Three towers and other buildings at Karak destroyed. Tafilah suffered similar damage. Flooding and building collapses in Ramla. Felt in Gaza, Ludd, and Qaqun. The Sultan in Damascus sent artisans, engineers and stonecutters to Karak to rebuild the city.
1458	Ambraseys et al. (1994); Amiran et al. (1994); Guidoboni and Comastri (2005)	Dead Sea/ Wadi Araba	Town walls collapsed, many houses, the government building, and citadel towers destroyed in Karak; 100 deaths. Minarets in Jerusalem, Ramla and Hebron collapsed. Shock felt in Cairo.
1546	Ambraseys et al. (1994); Amiran et al. (1994)	Dead Sea	Strong series of shocks felt in Jerusalem, Hebron, Gaza, Ramla, al-Karak, al-Salt and Nablus. Church of Holy Sepulchre in Jerusalem sustained damage. Five hundred people killed in Nablus
1588	Ambraseys et al. (1994)	Wadi Araba/ Red Sea	Houses in Cairo damage, St. Catherine monastery in Sinai destroyed. Looting in Aila (Aqaba)
1837	Amiran et al. (1994)	Dead Sea	Epicenter possibly near Safed, clefts in the ground, 2,100 people killed and buildings collapsed in Safed, Tyre, and Sidon. Moderate Damage in Nazareth, Haifa and Hebron. Damage in ‘Araba. Twenty houses collapsed in Karak. Blocks of bitumen (asphalt) floating in Dead Sea. Ford crossing from Lisan Peninsula to Masada disappeared.

Guidoboni et al. 1994; Guidoboni and Comastri 2005; Russell 1980, 1985). The events that most likely caused damage or ground rupture at Qasr Tilah occurred in 634, 659/660, 1068, 1212, 1293, 1458, and 1546 based on estimated epicentral location and the severity of damage in cities (especially the citadel of Karak) in close proximity to the site (Abou Karaki 1987; Ambraseys et al. 1994; Amiran et al. 1994; Ben-Menahem 1991; Guidoboni et al. 1994; Guidoboni and Comastri 2005; Russell 1980, 1985). We narrowed the larger list of Dead Sea/Wadi Araba earthquakes to the list of likely ground-rupturing earthquakes based on two criteria: documented ground rupture of a fault other than the Wadi Araba Fault (e.g., Jericho fault,

Jordan Valley fault), and historical reports of intensity and felt area (damage reports). An earthquake of 659/660 is likely located in the Jordan Valley, based on archaeological data from Saint John the Baptist monastery (Russell 1985). However, the historical records suggest that there may have been more than one earthquake during 659/660 (Russell 1985; Guidoboni et al. 1994). It is possible that one of these events caused ground-rupture at Qasr Tilah. Reports of major damage and casualties in the cities of Karak, At-Tafilah, Shaubak, and Aqaba in southern Jordan suggest that the earthquakes of 1068, 1212, 1293, 1458, and 1546 were possibly the result of rupture along the WAF. The earthquake of 1837, based on the historical records, likely ruptured along the Jordan Valley fault in the north (Abou Karaki 1987; Ambraseys et al. 1994; Amiran et al. 1994; Ben-Menahem 1991; Guidoboni et al. 1994; Guidoboni and Comastri 2005; Russell 1980, 1985).

We recognized evidence of four earthquakes in the sediments exposed in Trench A.7. Using relative dating, radiocarbon data, ceramic analysis and paleoseismic analysis, we correlate the archaeoseismic data with historical records to determine possible calendar dates for each seismic event.

Unit a caps the MRE fault trace. An Ottoman period musket ball at the base of unit a constrains the minimum and maximum age of the MRE from 1515 to 1918. Based on correlation with major earthquake catalogs, the MRE could have occurred on 1837, 1588, or 1546 (Abou Karaki 1987; Ambraseys et al. 1994; Amiran et al. 1994; Ben-Menahem 1991). The 1588 earthquake most likely occurred in the southern Wadi Araba or Gulf of Aqaba based on extensive damage to structures in the Sinai and in the northern Hejaz and therefore did not rupture the WAF (Poirier and Taher 1980; Ambrasey and Melville 1989). The 1837 earthquake caused massive destruction near Safad and Tiberias suggesting an epicentral source to the north and probably did not rupture the WAF (Ambraseys et al. 1994). Therefore, the most likely historical earthquake for the MRE at Qasr Tilah is 1546 earthquake. Ambraseys and Karcz (1992) have suggested that this was a minor M6.0 event whose devastation has been exaggerated.

The fault strands defining Event II is capped by unit d, which is radiocarbon dated to 986–1155 A.D. Thus, Event II could not have occurred in 1458, 1293, or 1212 (Abou Karaki 1987; Ambraseys et al. 1994; Amiran et al. 1994; Ben-Menahem 1991). The tenth to twelfth century date of unit d, suggests that the minimum age of Event II is tenth century. The historical earthquake catalogs suggest that only the earthquake of 1068 occurred in the Wadi Araba during the tenth through the twelfth centuries. Therefore, we have correlated the penultimate earthquake at the Qasr Tilah site to the 1068 event.

Unit e caps buries the fault strands that define Event III. The overlying unit d has a radiocarbon-constrained age range between the tenth to twelfth century, and the underlying units f, g, and h contain aqueduct rubble and potsherds from the seventh century. Therefore, the age of unit e is constrained to seventh to twelfth century. One earthquake in 873 (Ambraseys et al. 1994) reportedly occurred in the region in that time interval. However, based on the historical descriptions, the epicenter was likely located in the northern Hejaz (Ambraseys and Melville 1989). However, due to the sparse population of the Hejaz and Wadi Araba, the historical record of the earthquake maybe distorted or biased, thus the catalog may be incorrect (Ambraseys et al. 1994). The geological data, constrained by datable material in Trench A.7, suggests that the WAF ruptured between the seventh to tenth centuries, thus opening the possibility that the rupture was caused by the 873 earthquake.

The fault that defines Event IV is covered by units f and g. Archaeological evidence from the trench suggests that the site was not occupied past the early Umayyad period (661–700 A.D.). Event IV most likely occurred during occupation of the site in the seventh century. Multiple earthquakes occurred in the region and are reported as a combined seismic event given the date 659/660 (Russell 1985; Amiran et al. 1994; Guidoboni et al. 1994). It is likely that the event that required the repair of the northwest corner of the birkeh was followed in short succession by the event that ruptured the birkeh and the aqueduct, based on archaeological evidence found in pottery and stratigraphic contextual evidence identified in trench A.7. It is possible that the 634 event was responsible for the subsidence across the northwest corner of the reservoir at Qasr Tilah that was repaired. Thus, it is most likely that the earliest event identified in Trench A.7 caused the site to be abandoned, and may have occurred in one of the 659/660 earthquakes (Russell 1985; Guidoboni et al. 1994).

Conclusions

We have identified four earthquakes in the stratigraphic section and plans exposed in Trench A.7. Based on radiocarbon data and relative dating coupled with historical records, the earthquakes most likely occurred on: 659/660, 873, 1068, and 1546. However, historical records report large earthquakes in the Wadi Araba in 1212, 1293 and 1458 for which we saw no apparent evidence in Trench A.7. While it is possible that the earthquake record preserved in the deposits is incomplete, it is unlikely that the events that occurred in the thirteenth and fifteenth centuries are misidentified due to the eleventh century radiocarbon date from unit d, which is undeformed except by the most recent event. Because of the artifactual content (Ottoman musket ball) of unit b, which is cut by the MRE, it is unlikely that the MRE is older than sixteenth century. Thus, it is possible that overlying evidence of twelfth and fifteenth earthquakes has been eroded before the deposition of units a, b, and c. It is also possible is that the twelfth and fifteenth century earthquakes did not cause surface rupture on the WAF.

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